Zero-Emission Cargo Transport II:
San Pedro Bay Ports Hybrid & Fuel Cell Electric Vehicle Project

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South Coast Air Quality Management District
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[Project ID # elt158]

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Project Overview

Timeline

- Project Award: 10/1/14
- Contractor Kickoff: 12/16/15
- Project Completion: 9/30/21

Contractors & Projects

- BAE/CTE: Fuel cell range extended drayage truck
- TransPower: Fuel cell range extended drayage truck
- U.S. Hybrid: Fuel cell powered drayage truck
- Hydrogenics: Fuel cell range extended drayage truck
- BAE/GTI: CNG hybrid with Near Zero CNG Engine

Barriers & Challenges

- Fueling Infrastructure: Availability and location
- Costs: Fuel Cells, batteries and infrastructure
- System Integration: Safe and efficient deployment of the technology Barriers

Budget

- DoE: $10,000,000
- Funding partners: $7,467,473
- Contractors: $3,075,841
- Total Cost:$20,543,314

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Relevance: Goals & Objectives

2019/2020 Objectives

- Complete vehicle builds
- Operate portable hydrogen refueling for demonstration
- Continue vehicle demonstration and data collection & analysis

Results

- Six demonstration trucks including fuel cell range extended and CNG hybrid truck deployed
- Portable hydrogen fuel onsite is in operation
- Debugging and improvement while demonstrating by lessons-learned from the first demo trucks
- Vehicle performance data provided from demonstration trucks

Impact

- Pushing Zero Emission Technology and Industry Envelope by Demonstrating First Fleet of FCEV's in Drayage Service in California

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Remaining Challenges & Barriers

Fueling Infrastructure - Availability and location

- All temporary hydrogen fueling is in place and being used for the demonstration
- Secure hydrogen fuel supply will be a challenge – South Coast AQMD is working with partners on a solution (Renewable hydrogen station, Mobile refueler, retail stations)

System Integration: Safe and efficient deployment of the technology

- Six of seven vehicles are deployed including CNG hybrid truck
- Design improvement and system optimization
- Analyze data collected and secure reliability

Costs and Application

- Costs will remain a challenge for the near and mid term
- Penetration into mid or long range application (currently ~200 miles range)

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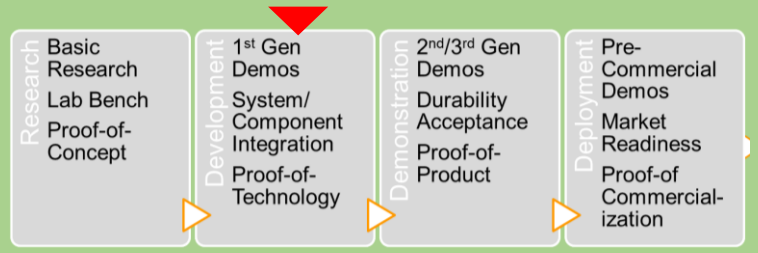
Approach

Vehicle Development and Deployment



	FUEL CELL TRUCKS				PHET/CNG
	TransPower	Hydrogenics (Cummins)	US Hybrid	BAE/Kenworth	
# of Vehicles	2	1	2	1	1
Platform	International	Freightliner	Kenworth T800	Kenworth T370	Kenworth T680
Mfg: Fuel Cell / APU	Hydrogenics	Hydrogenics	PureMotion	Ballard	CWI L9N NZE
Fuel Cell Power	60 kW	60 kW	80 kW	85 kW	n/a
Battery Capacity	125 kWh	100 kWh	26 kWh	100 kWh	100 kWh
Battery Chemistry	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion
Traction Motors	2x 150 kW	1x 320 kW	1x 320 kW	1x 420 kW	1x 420 kW
Range (per fueling)	200 miles	150 miles	150-200 miles	112 miles	150 miles
Fuel Cap.: H2 (kg) / CNG (DGE)	27 kg @350 bar	30 kg @350 bar	20 kg @350 bar	30 kg @350 bar	45 DGE
	Deployed		Deployed	Deployed	Deployed

In-use Demonstration and vehicle performance Analysis

TCO Analysis and Commercialization Roadmap

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Technical Progress – Hydrogen Stations

Portable hydrogen refueling at Port of LA demonstration site (San Pedro, CA)

- Air Products supports the fueling station at TTSI (end-user)
- Equipment will remain active throughout the vehicle demonstration period for all vehicles under this program
- Site features 2x Air Products HF-150 mobile refuelers:
  - Total capacity: ~300 kg/day
  - Pressure: 350 bar
- Third HF-150 mobile refueler available on demand

Photo: CTE

Mobile Refueler – San Pedro

Technical Progress – Fuel Cell Truck

In-use Demonstration

- **Project Management for Phase 2 (Demonstration and Data Collection)**
  - CTE is responsible for overall project management as well as detailing demonstration support and data collection activities conducted by the project team
- **Vehicle In-Service Operation and Data Collection**
  - The vehicle was delivered to the operator, TTSI, at the Port of LA on February 4th, 2019.
  - The vehicle has accumulated almost 2,000 miles in revenue service operation
  - Kenworth and BAE provide support the vehicle during operation at the Port of LA, including collecting and analyzing performance data
  - Ballard provides support for fuel cell diagnostics and service activity during the demonstration period

Performance at 65,000lbs GCW

Parameter	Target	Measured
Range (Total)	112 miles	216 miles
Range (Elec)	n/a	27 miles
Top Speed	70 mph	70 mph
Startability	30%	20% +
Gradeability:		
Speed 6.5%	35 mph	36 mph
Speed 5.0%	40 mph	40 mph

Photo: PACCAR

Starting on 20% slope at 80,000 GVW

Technical Progress – Fuel Cell Truck

In-use Demonstration

- FC#1
  - Deployed at Q4 2017
  - Rebuilt and entering recommissioning – focused on battery, fuel cell operation

- FC#2
  - Deployed at Q2 2019
  - Improved NMC battery packs: Nissan Leaf battery (44kWh/pack, 176kWh total)

FC#1 at Fuel Cell Expo, Nov. 2017

Towing rolls of steel to the San Ysidro border crossing

FC#2 at TTSI

Technical Progress – Fuel Cell Truck

In-use Demonstration for both FC #1 and #2

- US Hybrid's first and Second fuel cell truck has been deployed and demonstrated at TTSI
- H2 tanks capacity of FC #2 increased to 35kg at 350 bar – up to 250miles at 80k GVWR, 300miles at 45k-lbs.
- Battery system & Cooling upgraded
- Truck Auxiliary/cooling loads reduction by 20%

FC #1, #2 in demonstration

Technical Progress – Fuel Cell Truck

CEC truck progress – Identical to ZECT II truck

- Hydrogenics is acquired by Cummins
  - Cummins engineering and project management resources have been brought in to complete the project
  - Truck will be covered by Cummins service and support during demonstration
- Truck build complete and commissioning in progress (250 mi. accumulated)

CEC (ARV-15-002) truck

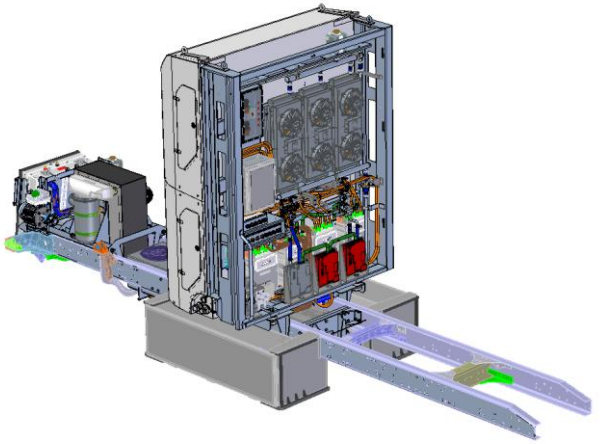
Truck Specifications

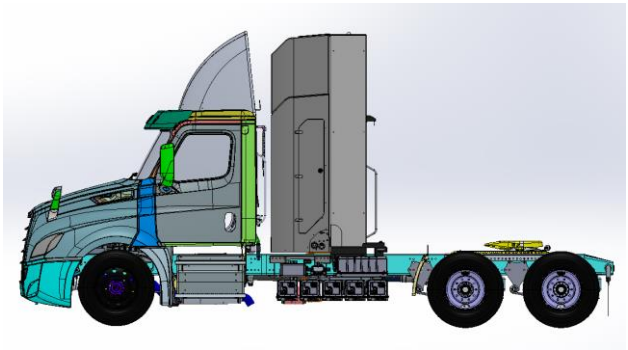
Item	Target Specification
Chassis	MY2020 Freightliner Cascadia Day Cab
GVWR	80,000 lbs. (Class 8)
Fuel Cell Power System	Hydrogenics CelerityPlus 60 kW
Electric Drive	Siemens ELFA® Drive System
Battery	XALT Energy XMP76P 106 KWh
System Voltage	650 V
Hydrogen Storage	23.5 kg @ 350 bar
Refuel Time	10-15 minutes
Expected Range	150 mi. depending on duty cycle

Technical Progress – Fuel Cell Truck

ZECT II truck progress

- System design in final stage and all major components have been ordered
- Design improvements from CEC truck include:
  - Adapting layout and packaging to MY 2020 chassis
  - Battery upgrade from prototype to production pack. Different battery chemistry (from LTO to NMC) and cooling needs require update to thermal management system
  - Improving power steering pump compatibility issues with motor to solve pump stalling
  - Improved packaging of thermal management system and power electronics rack for better manufacturability
  - Different motor inverter for better performance and lower weight
- Truck build and commissioning scheduled in Q3 2020.





3D modeling work for ZECT II truck

Technical Progress – CNG Hybrid Truck

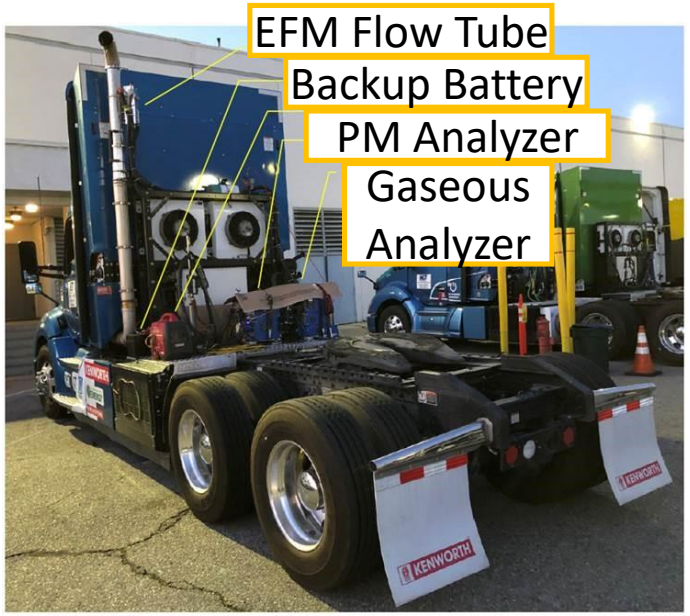
In-use Demonstration

- Cummins Westport Inc. Near-Zero L9N Engine
- Completed the reliability testing at Paccar Test Center in September 2019
- Delivered to TTSI in October 2019
- Accumulated approx. 5000 miles in revenue service since November 2019
- Positive driver feedback
- Completed portable emissions (PEMS) testing in March, data analysis in progress
- In-service and baseline vehicle (Diesel, CNG) data collected
- Analysis of collected data in process

Parameter	Target	Measured
Range Total	150 miles	284 miles*
Elec-Only	20 miles	26 miles
Top Speed	62 mph	65 mph

- Note: 80,000 lbs. GCW, *Measured from test track

Reliability and range testing at Paccar Test Center



PEMS testing setup

Demonstration Issues and Lessons Learned

Technical Issues while Development and Demonstration

- **Typical issues of a demonstration**
  - Blown fuses, damaged sensors
  - Data Upload Technical Difficulties

- **New technology specific improvement & issues**
  - Software Updates
  - Battery Disconnect Failures
  - Blown Internal Battery Fuses
  - Inconsistent Traction Motor Resolver
  - Transmission Shift Position Sensor
  - Fuel cell coolant contamination
  - Cooling system control for fuel cell stack
  - Leakage of Hydrogen tank valves

High
Moderate
Low

Deteriorated FC coolant reservoir cap


Inspection of Battery Fuses


Transmission Repair

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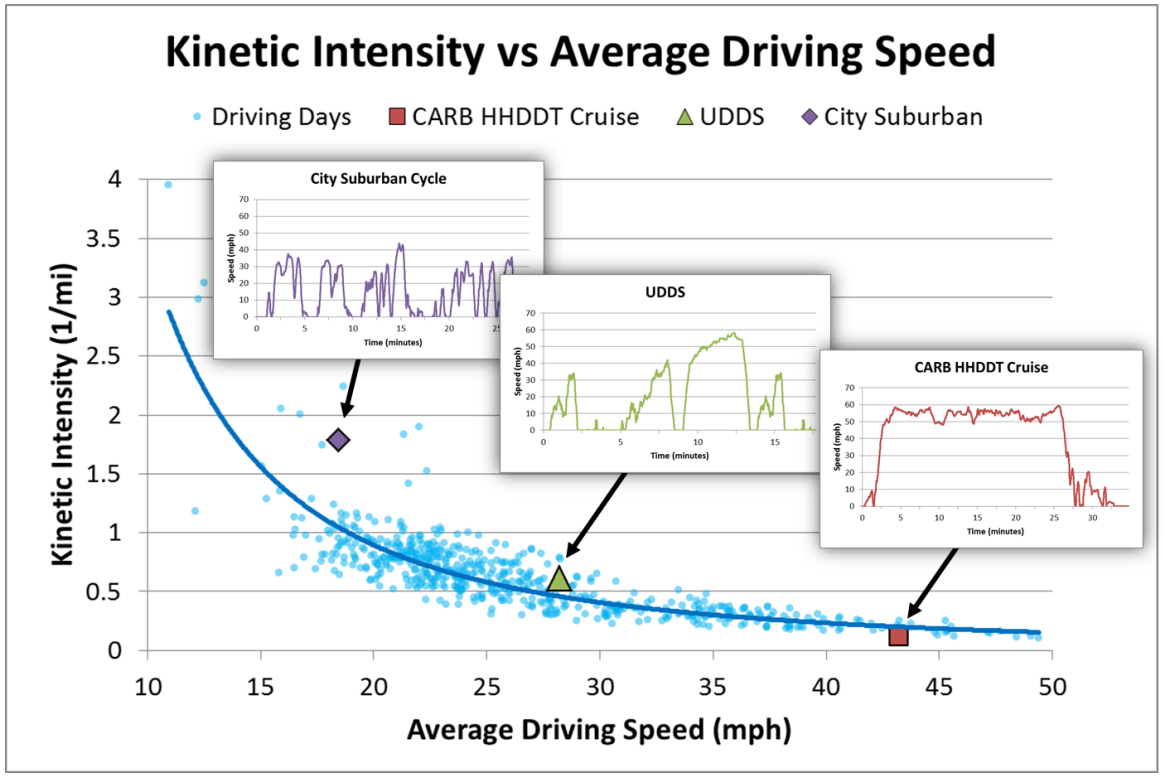
Demonstration Issues and Lessons Learned

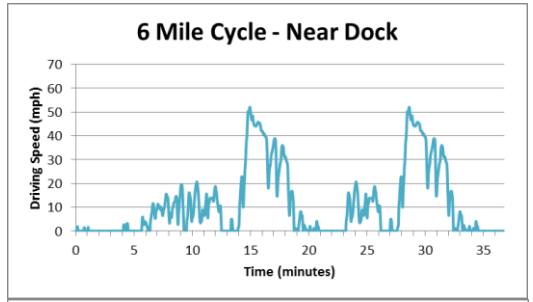
Lessons-Learned from Development and Demonstration

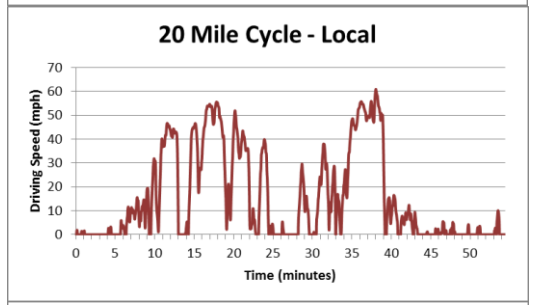
- Positive feedbacks from drivers for drivability and performance, but reliability is an issue
- Supply base is not ready and suppliers do not have broad knowledge in applications
- Too many connections (HV, LV, CAN, Cooling) and routing design is integral to chassis layout
- Cooling (particularly for FC) is challenging
- Battery technology and management systems for heavy-duty vehicles are evolving and maturing
- Power electronics firmware needs to become more automated
- Design validation is required for single larger FC stack and modular multi-stack

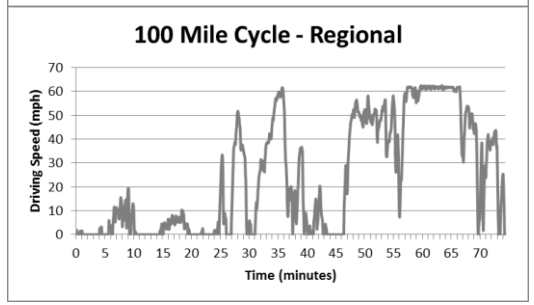
Data Analysis – Baseline Trucks

- Class 8 Tractors
- Multiple OEMs - Navistar, Volvo, Mack, Freightliner, Peterbilt & Sterling
- Trip segments grouped by maximum radius distance from the Port of LB
- Processed using NREL's DRIVE tool









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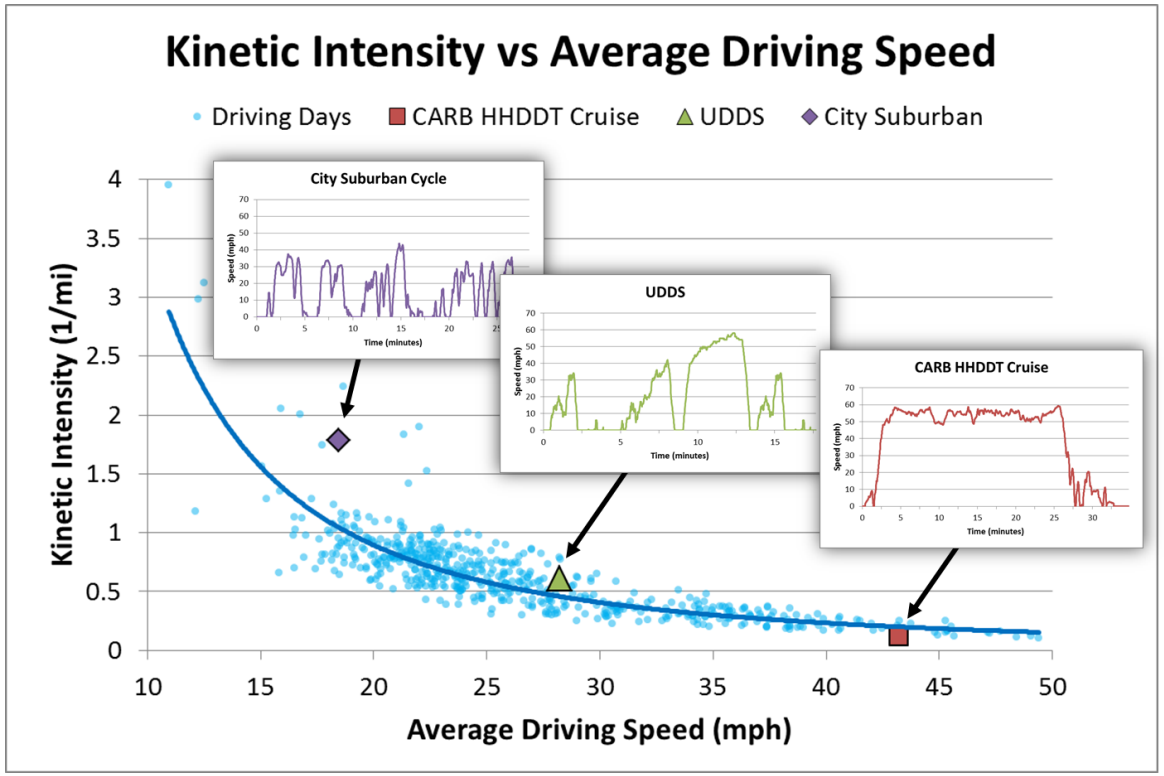

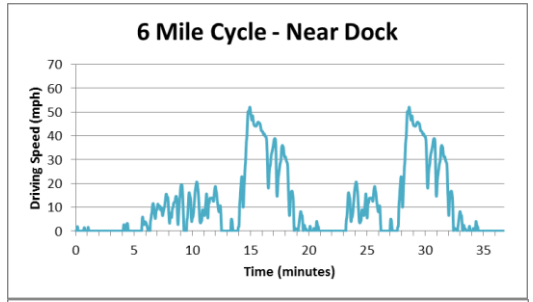

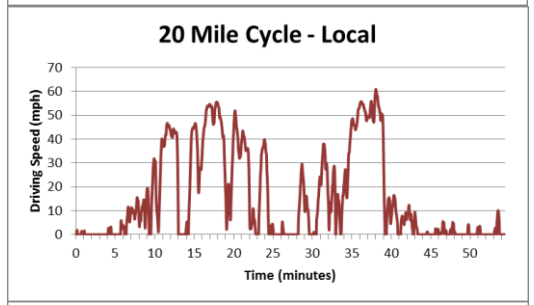

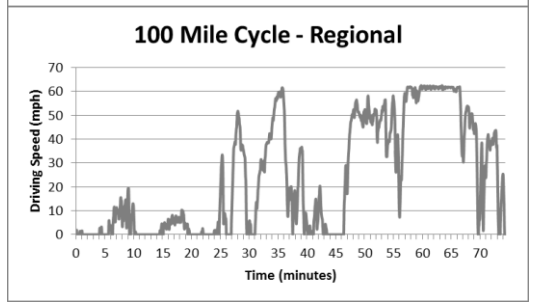

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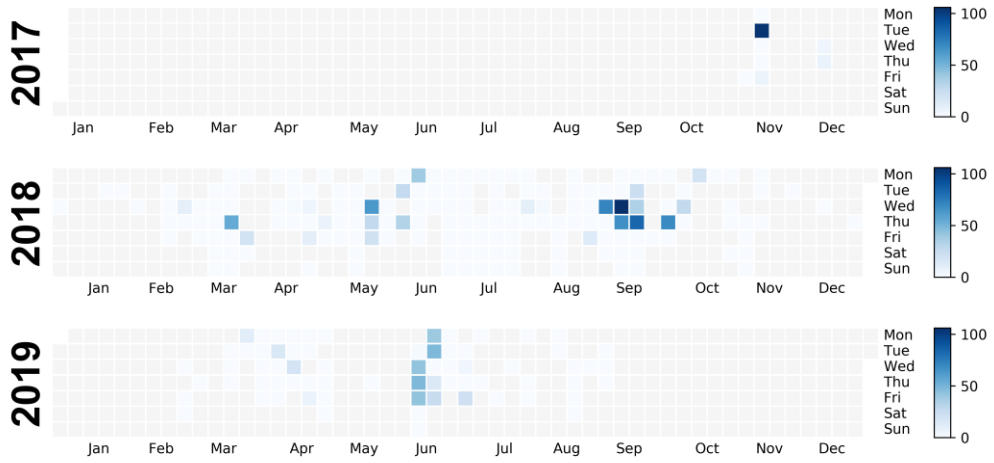
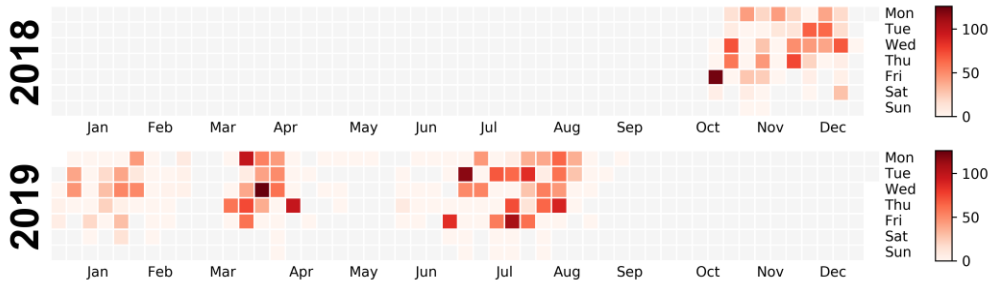
Data Analysis – Daily Miles Traveled

TransPower – HEDD1

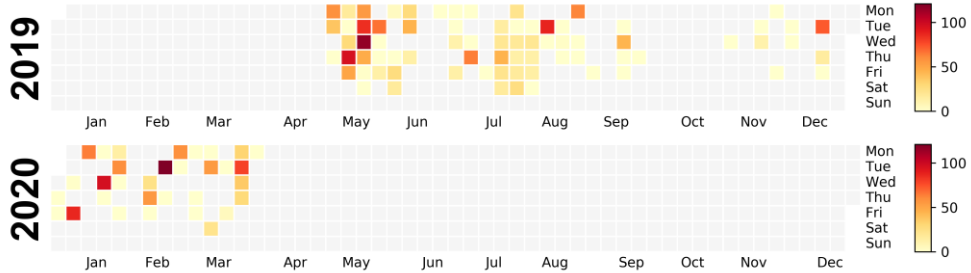


TransPower – HEDD2

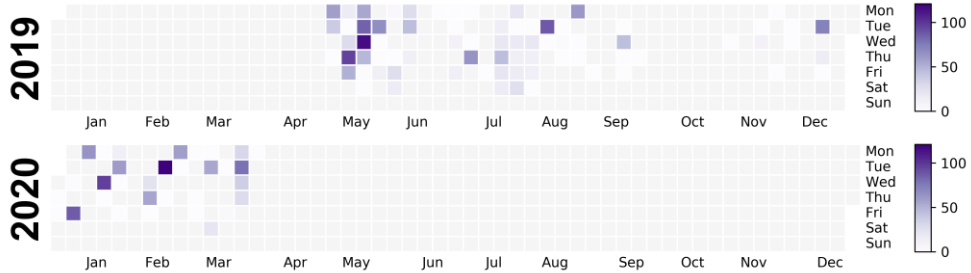


*calendar plots include all received data files

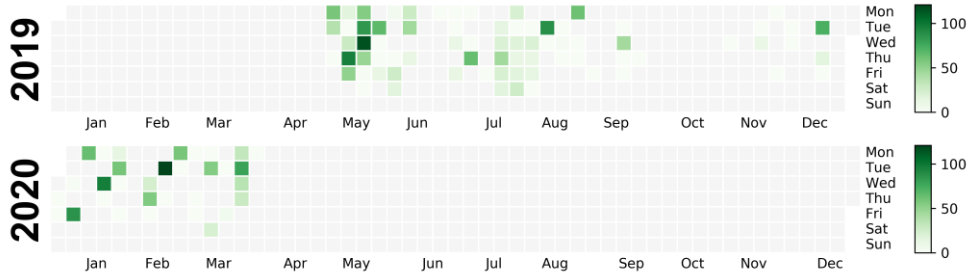
US Hybrid – FC359



US Hybrid – FC365



Kenworth – ZECT



Data Analysis – Summary Table

Metric	Units	Baseline Conventional*	TransPower HEDD1	TransPower HEDD2	US Hybrid FC359	US Hybrid FC365	Kenworth ZECT
Date Range		2014-2015	11/3/2017 – 9/5/2019	10/24/2018 – 9/9/2019	5/6/2019 – 3/30/2020	5/8/2019 – 3/2/2020	6/13/2019 – 1/7/2020
Number of recorded vehicle days	#	557	152	94	106	31	29
Max daily distance	mi	—	106.5	126.9	122.7	28.0	123.3
Avg daily distance	mi	127.9	5.8	21.0	21.0	6.4	25.1
Avg operating time (key-on)	hr	10.1	10.0	5.8	2.0	0.7	3.4
Avg driving time	hr	4.5	0.3	1.1	0.9	0.3	1.2
Avg speed	mph	14	1.3	3.5	7.0	6.2	5.1
Avg driving speed (speed>0)	mph	26.5	10.6	14.4	17.8	14.1	12.3
Kinetic intensity	1/mi	0.64	1.4	0.8	1.6	2.7	2.4
Avg stops/day	#/day	124.9	14.2	62.9	50.0	17.4	86.8
Avg stops/mi	#/mile	1.38	24.6	18.1	13.5	17.7	—
Median stop duration	sec	40.8	346.7	39.2	9.5	27.4	8.3
Avg daily fuel use (H2)	kg	—	—	—	3.2	0.9	5.1
Avg daily fuel use (diesel equiv.)	gal	23.7	—	—	2.8	0.8	4.5
Avg fuel economy (diesel equiv.)	mi/gal	5.7	—	—	8.3	9.5	7.4
Avg fuel cell efficiency	%	—	—	—	53.3%	56.4%	52.3%

**ZECT II milestone report: Baseline Vehicle Data Collection and Analysis Report – Port Drayage*

Future Research

1. **Collect real operation data from demonstration**
   - Continue demonstration to collect more data
   - Analyze vehicle performance data by NREL
     - GPS data,
     - average daily VMT,
     - Kinetic intensity
     - Fuel economy
   - Compare to conventional truck data with similar operating route

2. **Analyze Total Cost of Ownership**
   - Vehicle, Fuel, Maintenance cost
   - Assessment of infrastructure cost
   - Assessment of operating penalty (time, weight)

3. **Establish a roadmap for commercialization roadmap**
   - Market development strategy
   - Leverage the knowledge from this demonstration for other projects
   - Accelerate participation of OEMs

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Response to Reviewers' Comments

Reviewer's comment #1

The reviewer recommended to see more standardized testing across vehicles to enable more direct performance comparisons between them (e.g., with consistent vehicle loads and duty cycles). The reviewer remarked it would also be good to have at least several months of data collection (if not indefinite as long as the vehicles remain in operation) to get a good picture of their in-use performance and to compare this against the performance of comparable conventional trucks.

The contract has been extended by September 30th 2021 without additional cost. Our project team will continue the demonstration and data collection. NREL provided baseline data collected from conventional diesel trucks and preliminary result for comparison of Alt. fuel trucks and conventional diesel trucks.

Our project team is aware that this comparison analysis addressing duty cycle, efficiency, range and payload capacity is one of most critical accomplishment of this project.

Port of Los Angeles and Long Beach set a goal of full zero-emission in all equipment inside the ports. The result from this project will help customer to make their decision for purchasing zero-emission vehicles.

These tasks will enable to establish a roadmap for commercialization in the end of project.

Reviewer's comment #2

The reviewer suggested it could be reasonable to see some level of perpetual cost increment between these zero- and near-zero-emission vehicles and comparable conventional alternatives given the fuel diversification, energy security, and emissions benefits of the new technologies, but the roadmapping exercise should at least seek to understand what that cost increment is today and what it could be in the future.

Our project team will establish a roadmap for commercialization in the end of the project. This roadmap will cover analysis of operation cost including fuel and maintenance collected from actual demonstration as well as TCO assessment including vehicle, infrastructure, operational penalties.

Summary

- Temporary hydrogen refueling are supporting vehicle testing and demonstration
  - Assessment of feasible pathway for hydrogen fueling in near and long term: Mobile refueler, Renewable hydrogen station
- Six vehicles including Two fuel cell trucks from TransPower, Two from US Hybrid, one from Kenworth and one CNG Hybrid truck from Kenworth
- Hydrogenics(Cummins) truck will be deployed in Q3 2020
- Demonstration has been impacted by COVID-19
- Continue demonstration and data analysis for comparison to conventional diesel trucks
- TCO analysis and commercialization roadmap will be accomplished
- Longer range truck and more OEMs' participation is required

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